STAFF SUMMARY SHEET

	TO	ACTION	SIGNATURE (Surname), GRADE AND DATE		TO	ACTION	SIGNATURE (Surname), GRADE AND DATE
1	DFAN	sig	Tucker, Lt Col, 13Mar12 for Col Barlow	6			
2	DFER	approve	Brent A Richter, Col 15 Mar 2012	7			
3	DFAN	action	Chase Guarnaccio, C1C, 03/13/12	8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
Guarnaccio, C1C		333-6836	ccg	20120315

SUBJECT	DATE
Clearance for Material for Public Release USAFA-DF-PA- 123	20120313

SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND. Authors: C1C Matt Thompson, C1C Chase Guarnaccio, Dr. Martiqua Post

Title: Investigation of Rocket Based Combined Cycle Design Modifications to Improve Cmo and Cmα at Subsonic Speeds

Circle one: Abstract Tech Report Journal Article Speech [Paper] Presentation Poster Thesis/Dissertation Book Other: ____________

Check all that apply (For Communications Purposes):

[] CRADA (Cooperative Research and Development Agreement) exists

[] Photo/ Video Opportunities [] STEM-outreach Related [] New Invention/ Discovery/ Patent

Description: This investigation tested various design modifications to the Rocket Based Combined Cycle (RBCC) to achieve a less negative pitching moment coefficient at an angle of attack of zero degrees (Cmo) thereby allowing the RBCC to trim at a lower angle of attack. The design modifications tested consisted of adding a scab to the bottom of the RBCC, decreasing the wing camber through wing twisting, and canting the vertical stabilizers with and without adding an incidence angle to the stabilizers. Each modification was tested 0.3 Mach with an angle of attack sweep from -4° to 28° and at 0.5 Mach with an angle of attack sweep from -4° to 22°. The results show that an increase of 80.4% in the value of Cmo can be achieved through a combination of the wing twist modification along with the camber change modification made to the body of the RBCC due to the scab. The camber of the RBCC body was reduced by 22.1%, the wing camber at the root reduced by 152.4% and the wing camber at the tip reduced by 153.4%. All of this resulted in the aforementioned increase in Cmo. The results also show that the stability of the RBCC can be increased by 19.1% through the canted vertical stabilizer design modification.

Release Information: To be presented at the AIAA Student Paper Competition, Boulder CO, April 4-6, 2012

Previous Clearance information: (If applicable): Mr Barry Hellman, AFRL/RBSI, has indicated no problem with publishing RBCC data as long as contractor information in not discussed.

Recommended Distribution Statement: Distribution A: approved for public release, distribution unlimited

3. DISCUSSION.

4. RECOMMENDATION. Sign coord block above indicating document is suitable for public release. Suitability is based solely on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy.

Thomas E. McLaughlin

Thomas E. McLaughlin, Ph.D.
Director, Aeronautics Research Center

Investigation of Rocket Based Combined Cycle Design Modifications to Improve C_{m_o} and C_{m_α} at Subsonic Speeds

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This investigation tested various design modifications to the Rocket Based Combined Cycle (RBCC) to achieve a less negative pitching moment coefficient at an angle of attack of zero degrees (Cm_o) thereby allowing the RBCC to trim at a lower angle of attack. The design modifications tested consisted of adding a scab to the bottom of the RBCC, decreasing the wing camber through wing twisting, and canting the vertical stabilizers with and without adding an incidence angle to the stabilizers. Each modification was tested 0.3 Mach with an angle of attack sweep from -4° to 28° and at 0.5 Mach with an angle of attack sweep from -4° to 22°. The results show that an increase of 80.4% in the value of Cm_o can be achieved through a combination of the wing twist modification along with the camber change modification made to the body of the RBCC due to the scab. The camber of the RBCC body was reduced by 22.1%, the wing camber at the root reduced by 152.4% and the wing camber at the tip reduced by 153.4%. All of this resulted in the aforementioned increase in Cm_o. The results also show that the stability of the RBCC can be increased by 19.1% through the canted vertical stabilizer design modification.

Nomenclature

ac	=	aerodynamic center, inches
A_x	=	axial force in the x direction, lb_f
cg	=	center of gravity, inches
C_D	=	drag coefficient
C_L	=	lift coefficient
C_l	=	rolling moment coefficient
Cl_β	=	lateral static stability derivative
Cm	=	longitudinal moment coefficient
Cm_α	=	longitudinal static stability derivative
Cm_o	=	pitching moment coefficient at 0° angle of attack
Cn	=	yawing moment coefficient
Cn_β	=	directional static stability derivative
CP	=	center of pressure
D	=	drag, lb_f
i_{cvs}	=	incidence angle of canted vertical stabilizer, deg
i_H	=	incidence angle of horizontal stabilizer, deg
L	=	lift, lb_f
M	=	Mach number
M_l	=	moment coefficient, in-lb_f
N_1	=	force coefficient forward of force balance cg the z direction, lb_f
N_2	=	force coefficient aft of force balance cg the z direction, lb_f
P	=	static pressure, psi
P_T	=	total pressure, psi
$RBCC$	=	Rocket Based Combined Cycle
Re	=	Reynolds Number
RBS	=	Reusable Booster System
SWT	=	Subsonic Wind Tunnel

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T = total temperature, °F
X' = force coefficient in the x direction, lb_f
Y_1 = force coefficient forward of the force balance cg in the y direction, lb_f
Y_2 = force coefficient aft of the force balance cg in the y direction, lb_f
α = angle of attack, deg
α_{trim} = trim angle of attack, where $Cm_o = 0$, deg
β = sideslip angle, deg
δ_e = deflection of elevator, deg

I. Introduction

The Rocket Based Combined Cycle (RBCC) concept vehicle was designed to fulfill the need for a Reusable Booster System (RBS). The RBS program requires that a system be able to launch a payload into orbit, return to earth horizontally, and launch again in less than 48 hours. Conceptually, a RBS will utilize a rocket or air-breathing engine to propel it into the upper atmosphere. A disposable booster will deploy the payload into orbit while the main reusable booster glides back to Earth. This allows for the main booster to avoid re-entry into the Earth's atmosphere. Avoiding the extreme temperatures of re-entry allows the RBS to be available for reuse in less than 48 hours[1]. A concept is diagrammed in Figure 1. Air-breathing and rocket based delivery systems were investigated by Air Force Research Laboratory. It was determined that a rocket based delivery system with scramjets was the most viable solution.

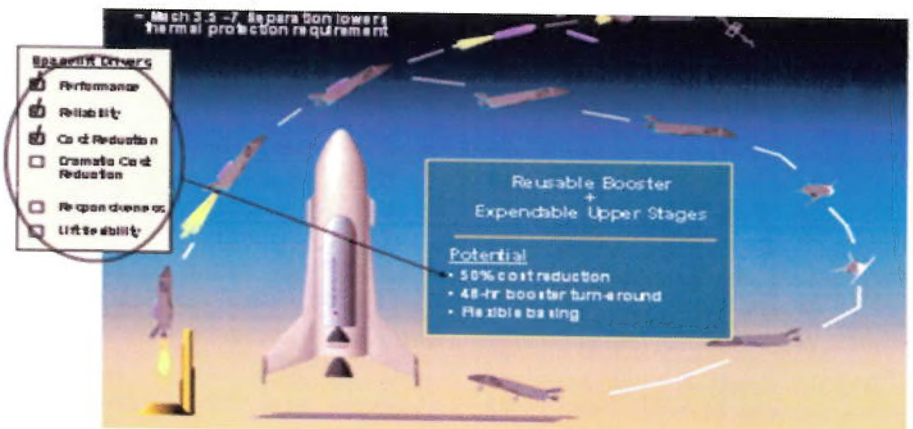

Figure 1. RBS Concept[1]

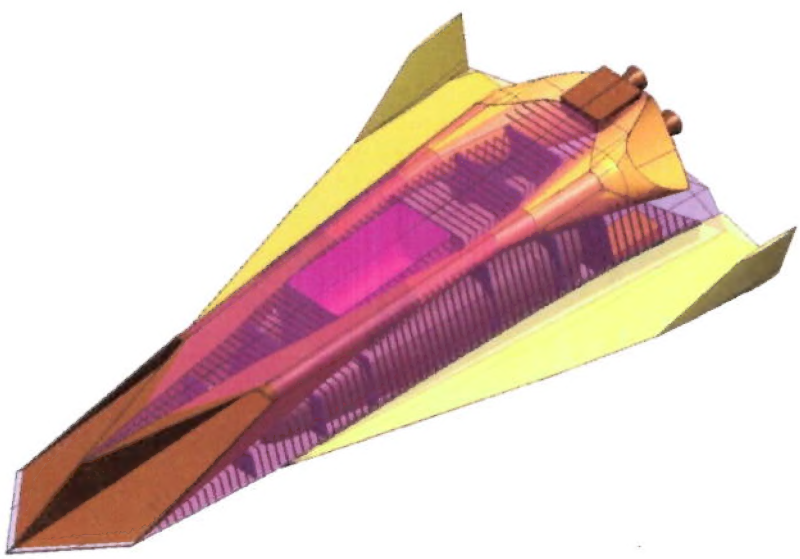

Figure 2. RBCC Designed by Astrox[2]

More specifically the design of the RBCC is an integrated rocket and scram-jet delivery system as depicted in Figure 2. The RBCC uses a rocket booster in a vertical takeoff to reach approximately Mach 3 and then the scramjet (air breathing) engines located on both sides of the RBCC activate and accelerate the RBCC to about Mach 10. At this speed the RBCC reaches the upper edge of the atmosphere where the payload detaches and the expendable upper stage rockets deliver the payload into orbit while the RBCC returns and lands horizontally. Using the upper stage rocket to insert the payload into orbit allows the RBCC to avoid full re-entry temperatures while still delivering its payload. Previous testing done on the RBCC analyzed the landing phase, the subsonic flight regime of the RBCC. This research, performed at the United States Air Force Academy's Subsonic Wind Tunnel discovered that the RBCC has a high level of instability in pitch. This instability can be shown in Figure 2, pitching moment coefficient, C_m, versus the angle of attack, α.[3]

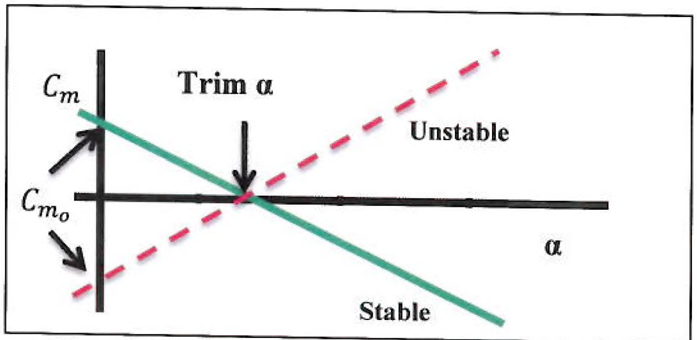

Figure 3. Pitching Moment Coefficient vs. Angle of Attack

A positive slope in Figure 3 signifies an unstable aircraft because as the angle of attack increases it is desirable that the pitching moment coefficient be negative to restore the aircraft to zero degrees angle of attack. The y-intercept occurs at a position known as C_{m_o} which means, the pitching moment coefficient at zero degrees α. For this research, based on the requests of the customer, a C_{m_o} value of zero is desired. The RBCC which was tested previously had a negative C_{m_o}, which means that given the positive (unstable) slope of C_{m_α} the aircraft trims at a positive angle of attack.

The first concept which was considered is airfoil shape, or camber, and its effect on the pitching moment. The mean camber line of an airfoil marks the midpoint between the upper and lower surface. Positive camber is defined as having more area above the chord line than below. These differences in airfoil shape determine where the net lift, or center of pressure (CP), is along the length the airfoil. Positively cambered airfoils have a *CP* aft of the aerodynamic center (*ac*) which causes a negative (nose-down) pitching moment. Therefore, a positively cambered airfoil has a negative C_{m_o}.[4]

The next concept which was used is that horizontal surfaces behind the center of gravity (*cg*) have an effect on longitudinal stability. This effect is twofold. First, the additional horizontal area creates additional lift aft of the *cg* which decreases C_{m_o}. In addition to this effect and more beneficial for the purposes of this research, as the angle of attack increases more of the horizontal surface is exposed, increasing the lift it creates. This increase in lift aft of the *cg* increases stability as it is an increasingly negative moment for an increase in angle of attack.[5]

This report will document research conducted attempting to increase C_{m_o} as well as to improve the longitudinal stability of the RBCC. The research was conducted using angle of attack sweeps, varying side slip angles, different Mach numbers, and different RBCC configurations. These tests will provide data which will be used to construct pitching moment coefficient plots which will be used to determine the effectiveness of each configuration. The purpose of this project is to contribute to the development of the RBCC program through wind tunnel testing and data analysis of the aerodynamic coefficients and aircraft stability of design modifications which attempt to decrease design instability as well as move the C_{m_o} towards zero.

II. Set-up and Procedure

This research was conducted in the United States Air Force Academy's Subsonic Wind Tunnel (SWT) which is located in the Aeronautical Laboratory. This closed-circuit wind tunnel has a test section of 3 feet by 3 feet by 7 feet long. Inside this test section is a rotating plate fixed to the floor which has a variable angle of attack sting attached. This setup allows for models to be tested at varying angles of attack for set side slip angles. This test section is

separated from the work area by a Plexiglas window, hinged at the top edge, which opens with a hydraulic assist mechanism. The test section of the SWT is preceded by a stilling chamber which contains a thermocouple, total pressure probe, and a static pressure ring (located at the entrance to the test section). These devices collect temperature and pressure data for the airflow. A schematic of this test section is shown in Figure 4.

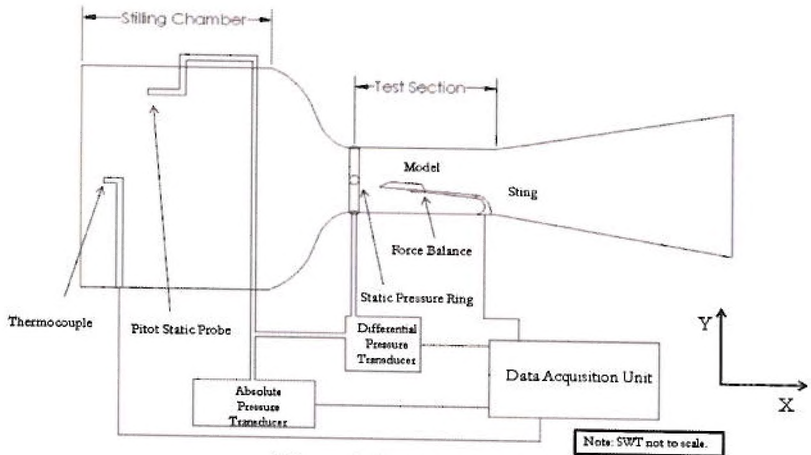

Figure 4. SWT Schematic

At the end of the sting a force balance is mounted, upon which the model itself will be secured. The force balance is manufactured by Task, serial number 35440, has an uncertainty of 0.25% of full scale loading and was last calibrated on January 28th 2011. This 100-lb rated force balance collects six different force measurements, two in the z-direction (N_1, N_2), two in the y-direction (Y_1, Y_2), one in the x-direction (X'), and one moment about the x-axis (R).

These forces are output, along with the data collected from the airflow, as raw voltages through the program, *Tunnel Vision*. *Tunnel Vision* takes the raw voltages and converts them into forces and pressures and then computes the aerodynamic coefficients to analyze them in both numeric and graphical form.

The voltages collected by these devices are input into the program *Reduces 1*. All of the *Reduces* programs were developed in-house to streamline the conversion of raw voltages to useable data for analysis. *Reduces 1* uses the calibration data from the wind tunnel equipment and force balance to output the true air properties as well as the force components from the force balance. This data is combined with geometric characteristics of the aircraft and the orientation of the sting in *Reduces 2* to calculate the aerodynamic coefficients. The characteristics input are the reference area, moment reference center, aerodynamic chord, and the x, y and z displacement between the center of gravity for the force balance and the model.

The coefficients produced by *Reduces 2* are then used in *Reduces 3* to produce plots comparing the different coefficients to different measurements such as the angle of attack and Mach number using Excel as the main post processing software. These curves are augmented by an uncertainty analysis performed on the force balance, which allows for error bars to demonstrate the amount of total error based on the aerodynamic coefficients used to generate the plots.

The following procedures were followed during experimentation to ensure consistent testing. An F-16 model was used to verify the calibration of the force balance before any of the testing is performed. This was done because an extensive record of force balance data has been accumulated for the F-16 model. After the calibration was complete, the F-16 was removed and replaced with the RBCC model which was securely fastened to the force balance using a set screw in the lower surface of the fuselage. The model was then oriented in the initial position for the test. When this was complete the wind tunnel door was closed and latched. A zero air tare run was then conducted. The air off data was used in *Reduces 1* to remove the effects of the models mass from the calculations. The desired test was then performed with a particular RBCC configuration and data was collected. This data was checked for validity by comparing it to similar tests and the clean configuration test of the RBCC to ensure that the obtained values are reasonable. The model was then reconfigured or the same configuration was run under different conditions. These runs were controlled through *Tunnel Vision,* which in addition to its *Reduces* programs also controls the stings computerized motor. Table 1 documents the various test conditions while Table 2 lists the modifications which were tested.

Table 1. Test Conditions for Design Iterations

Mach #	Reynolds #	Angle of Attack Sweep	Side Slip Angle
0.3	911, 900	-4° to 28°	0°, 5°, 10°
0.5	1,480,000	-4° to 22°	0°, 5°, 10°

Table 2. Test Matrix Design Iterations

Design Iteration	**Modification Made**
Closed Inlets	Seal off inlets
Deflected Body Flaps	±10°, ±20°, ±30°
Modified Fuselage Camber	Add lower scab, -4° upsweep using lower body flap
Modified Wing Camber/Twist	Twist wing -2.5° and reduce camber by 50%
Canted Vertical Stabilizer*	Baseline, 30°, 45°

Note: Every iteration of canted vertical stabilizer will also have an incidence angle of 0° or -3°.

Research was also conducted in the USAFA Water Tunnel. This research consisted of photographing the upper surface of the RBCC while using a dye wand to mark areas of the flow. This "flow visualization" provided useful information on the location of vortices and points of flow stagnation that could be mitigated by potential design changes.

III. Results and Discussion

To understand the results of the conducted research it is important to first understand the design iterations which were created and the intent of each of these iterations. The previous table, Table 3, lists the modifications. The first two iterations were designed based on the specifications of the customer.

A. Modified Fuselage Camber

Modifying fuselage camber was achieved using two separate modifications. The first of these modifications is called a scab. A scab is, in essence, the addition of material to an area of the model. In the case of the RBCC, the scab was applied to the flat undersurface of the wing, giving the bottom a rounded appearance. This additional material decreases the mean camber of the fuselage, which is inherently positive due to the shape of the RBCC. The scab, seen in Figure 5, causes a 2.29% decrease in camber for the fuselage.

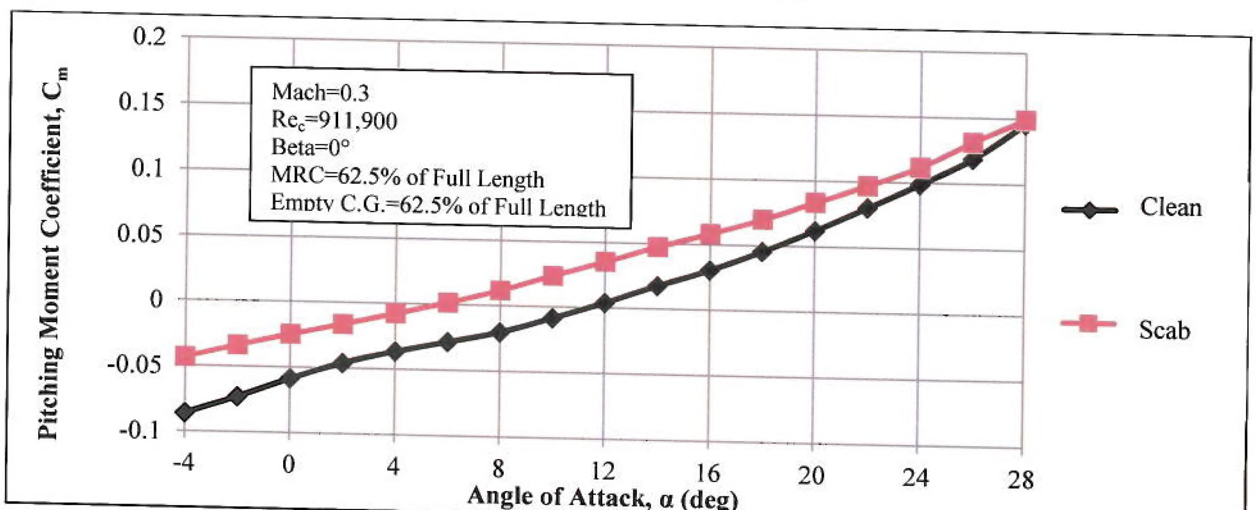

Figure 5. Scab vs. Clean Configuration

The results shown in Figure 5 show the increase in C_{m_o} due to the decrease in camber. There is a 57.3% increase in the original C_{m_o} value. There is also an increase in stability of 13.2%. While this design change shows promising results, it also presents a problem to the overall purpose of the RBCC. The scab increases the frontal area of the

RBCC which increases the drag; this drag increase may mean that the scab is not a viable option for the RBCC. Figure 6 illustrates the scab size and the resulting camber line change due to the scabs presence.

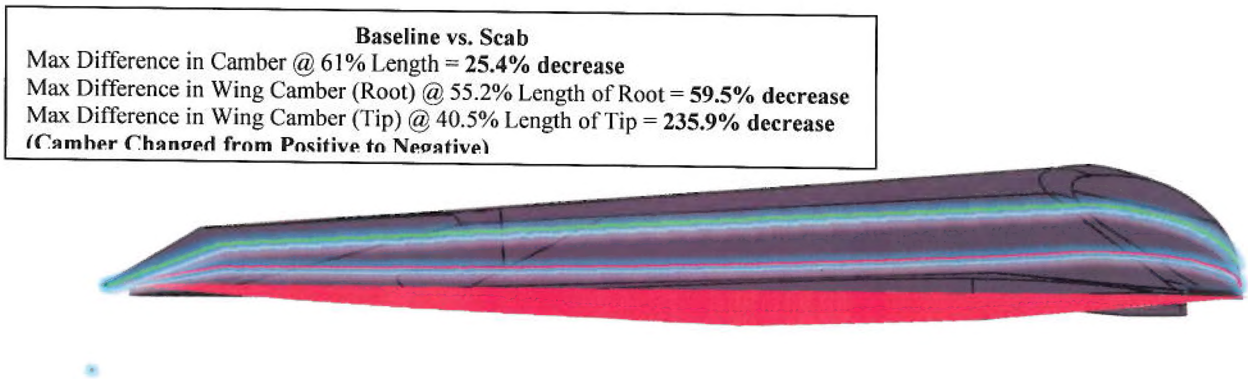

Figure 6. Comparison of Camber Line between Baseline Configuration (Green) and Scab Configuration (Red)

B. Modified Wing Camber

Modifying the wing camber was achieved by twisting the existing wing in such a way that the camber is decreased on the outboard portion of the wings. This was intended to increase stability by decreasing lift aft of the *cg* while also decreasing the inherent pitching moment of the cambered airfoil. For the RBCC the wing twist caused a decrease in camber of .9% at the root, a decrease of 2.5% camber at the tip, and a negative coefficient of lift at zero degrees angle of attack. The test results, shown in Figure 7, show an increase of x for C_{m_0} while showing little to no change in stability.

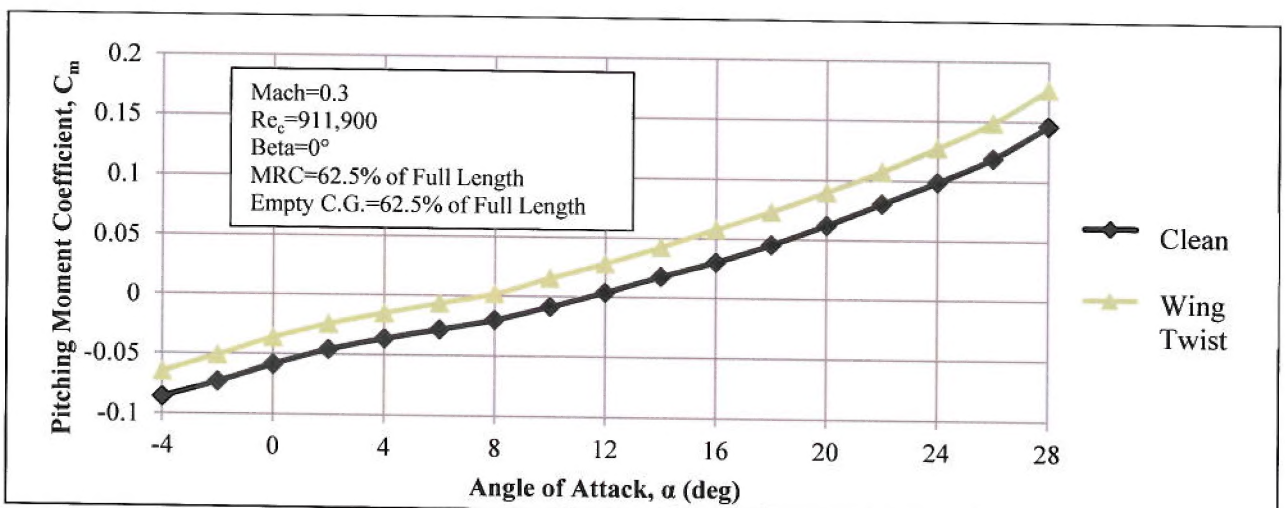

Figure 7. Wing Twist vs. Clean Configuration

The most promising aspect of this modification is the minimal change to the overall shape of the RBCC, which has been designed for conditions other than that of low speed gliding. This means that it is possible that this twist is a viable option for continued testing. Figure 8 illustrates the resulting camber line changes in the wing due to the wing twist.

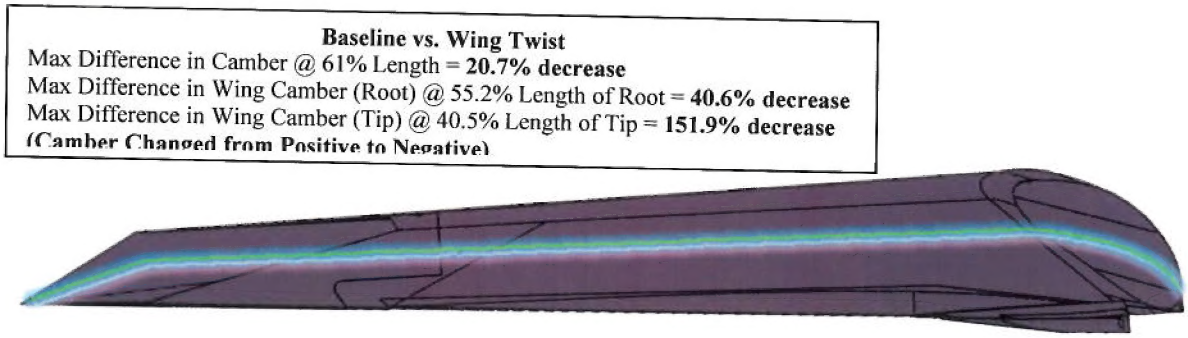

Figure 8. Comparison of Camber Line between Baseline Configuration (Green) and Wing Twist Camber Line (minimal change is not noticed visually)

C. Canted Vertical Stabilizers

Increasing the horizontal surface area aft of the RBCC's *cg* was accomplished by canting out the vertical stabilizers on the wing tips of the RBCC to both 30° and 45°, as well as giving them a negative incidence angle of -3°. These canted vertical stabilizers act more like horizontal tails while in their canted orientations, increasing the longitudinal stability. Four different orientations were tested; however, the trends for these orientations are nearly identical. Because of this, the results of the 45° with the -3° incidence angle, shown in Figure 9, can be extrapolated to the other orientations.

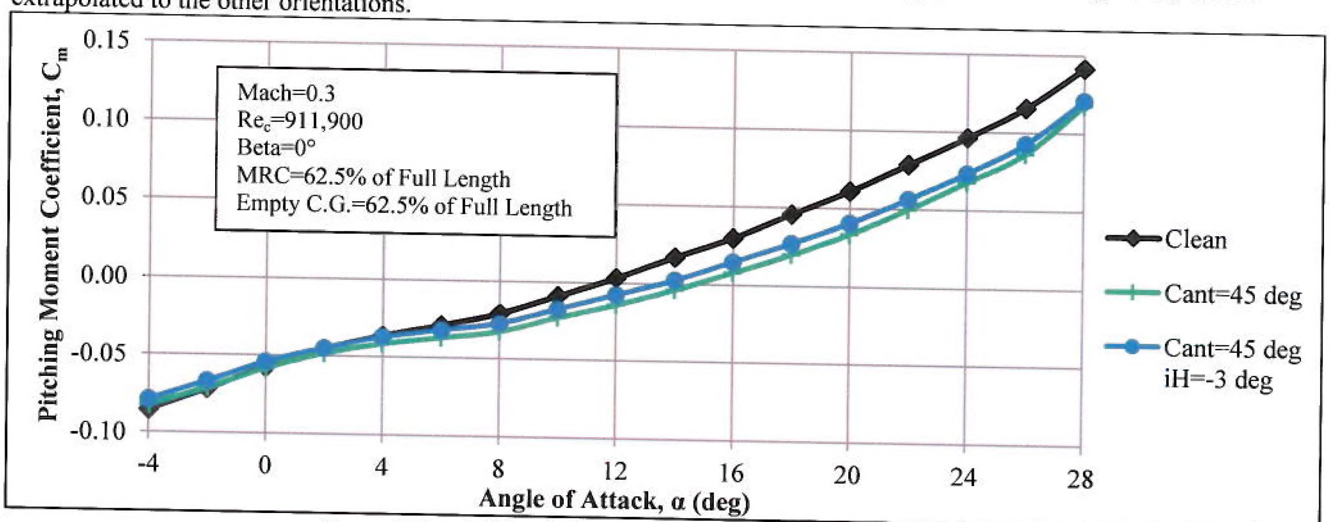

Figure 9. Canted Vertical Stabilizers vs. Clean Configuration

As expected, the change in C_{m_o} is minimal, while there is a noticeable decrease in instability. This decrease in instability is 19.1% compared to that of the normal configuration. It is possible that increasing the cant angle or the incidence angle could continue the trend seen in the tested orientations; however structural considerations are likely to be an issue as the angle of canting increases.

D. All-Star Concept

Based on the above results, most importantly the fact that none of the designs could drive C_{m_o} to zero, it was decided that additional testing needed to be conducted to confirm that various iterations could be combined to increase performance to the desired level. For this additional test it was decided that the scab and wing twist modifications should be combined as they had the most promising results. For this iteration a change was made to the scab to increase the ease of manufacturing and testing. The original scab extended under the inlets of the RBCC; however this required that the scab be made as a separate piece requiring additional mounting measures to ensure its integrity during testing. The new scab was designed to terminate at the leading edge of the wings. This new design modification, termed the "All-Star Wing" was tested under the same conditions as the original iterations. The results of this testing is shown in Figure 10.

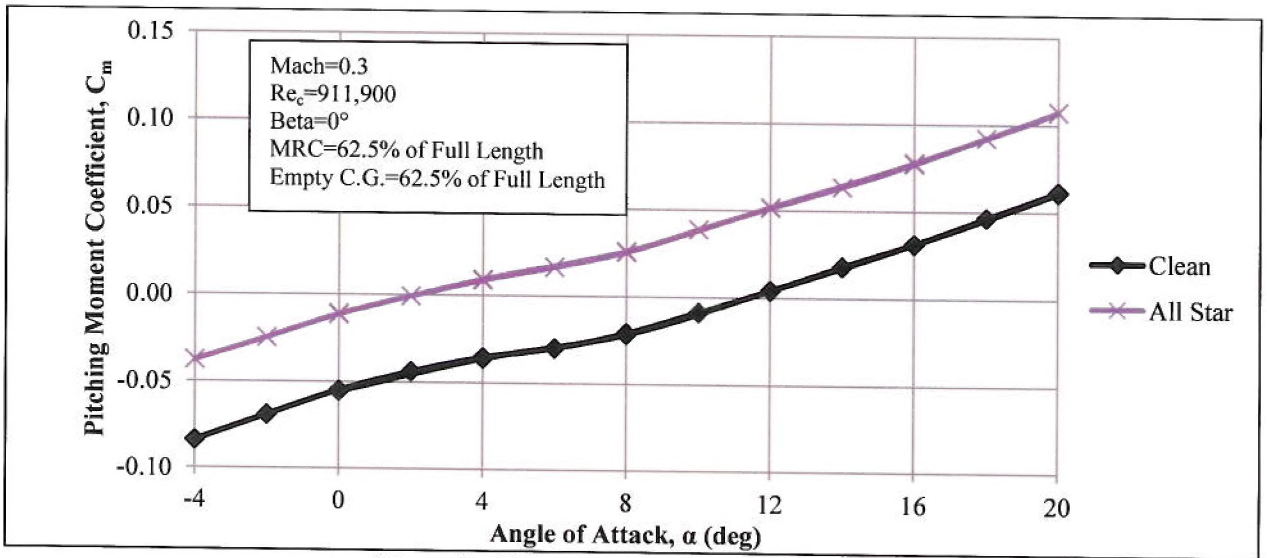

Figure 10. All-Star Wing vs. Clean Configuration

The All-Star wing shows an 80.4% increase in C_{m_o} with its final value of C_{m_o} being less than .01. A slight decrease in instability can also be seen due to the contribution of the "scab" modification. These results are extremely promising and show that a 2.24% decrease in fuselage camber and 2.35% decrease in wing camber at the wing root can allow for the RBCC to trim at nearly zero degrees angle of attack with minimal effect on any other aerodynamic coefficients. Figure 6 illustrates the scab size and the resulting camber line change due to the scabs presence. Figure 11 illustrates the All-Star scab size and the resulting camber line change due to the scabs presence as well as the wing twist.

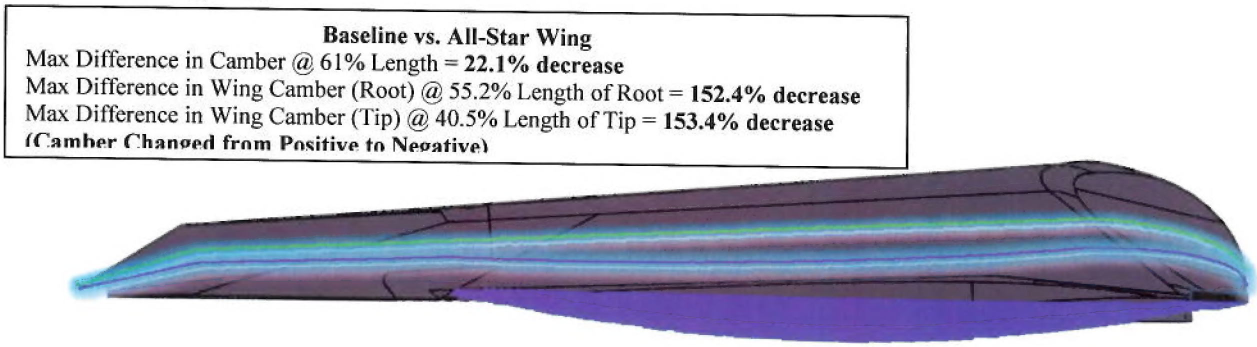

Figure 11. Comparison of Camber Line between Baseline Configuration (Green) and All-Star Configuration (Blue)

E. Summary of Results and Recommendations for Future Work

The results above can be quantified in the form of percent increases in C_{m_o} and C_{m_α} based the different design modifications made to the original RBCC. The results can also be analyzed based on the percent changes made to both the RBCC body and wing camber and the resulting effects on increase in C_{m_o}. Table 4 compiles the design modifications along with the percent increase or decrease in C_{m_o}.

Table 3. Compilation of Design Modifications and Percent Changes Made to C_{m_o} and C_{m_α}

Modification	Increase in C_{m_o}(% change with respect to clean configuration)	Decrease in C_{m_α}(% change with respect to clean configuration)
All-Star Wing	80.4	2.9
Scab	57.3	13.2
Wing Twist	37.8	-4.4
CVS (45°Cant, -3°i_{cvs})	7.11	19.1

Recommendations for future work are to collaborate with Astrox to find a more feasible way of decreasing the camber of the RBCC in order to increase C_{m_o} without interfering with a potential wave-rider design of the RBCC. Another aspect that needs to be investigated is the ground effect associated with landing the RBCC. Given the odd characteristics of the RBCC at subsonic speeds the ground effect is worth investigating as it is an integral part of the landing sequence. Another potential area of investigation is the addition of stability increasing modifications added to the All-Star wing concept in order to potentially increase the stability of the RBCC while at the same time raising C_{m_o}.

IV. Conclusion

The testing completed on the design modifications made to the RBCC show that the most advantageous solutions to increasing C_{m_o} and longitudinal stability are the wing twist, body scab, canted vertical stabilizers and closing off the inlets. All of these design iterations provided either an increase in C_{m_o} or an increase in longitudinal stability or both. The increase in C_{m_o} was deemed more important than increasing longitudinal stability because the main factor in the longitudinal instability of the RBCC is the location of the *ac* being forward of the *cg*. The design modifications that had the greatest effect on C_{m_o} were the scab and the wing twist combined into the All-Star wing. The All-Star wing's trim angle of attack was reduced to around 2°, which is an 83.3% decrease from the original 12° angle of attack of the clean configuration. The All-Star wing reduced the fuselage camber by 22.1%, the wing camber (root) by 152.4% and the wing camber (tip) by 153.4% resulting in an increase of C_{m_o} by 80.4% compared with the clean configuration. Therefore if the customer is able to reduce the camber of the fuselage and wing by this factor they can raise C_{m_o} by a factor of 80.4%. The separate scab and wing twist modifications also increased C_{m_o} by 57.3% and 37.8% respectively and their camber changes can be viewed in Table 5.

The canted vertical stabilizers and closing off the inlets provided an increase in stability for the RBCC with minimal changes to C_{m_o}. The 45° canted vertical stabilizers were able to decrease the slope of C_{m_α} by 19.1% and the closed inlets decreased C_{m_α} by 17.6%. It is important to remember the increased complexity of closing off the inlets for landing configuration and the small increase in stability given the large increase in complexity. The positive body flap deflections were able to decrease C_{m_o}, while the negative body flap deflections increased C_{m_o} though the change was very small given the size of the upper body flap. At the largest positive and negative body flap deflection of ±30° there was a 125.6% decrease in C_{m_o} and a 3.22% increase in C_{m_o} respectively.

All of the planned design modifications that were developed from the project purpose of raising C_{m_o} and increasing longitudinal stability have been tested in the SWT. All design modifications were tested at subsonic speeds in order to analyze the landing configuration portion of the RBCC's mission. These design changes have the potential to be combined together in order to achieve the desired C_{m_o} as demonstrated by the combination of the body scab and twisted wings. The longitudinal stability, although still a major problem, can be improved through the forward movement of the *cg* of the RBCC from its original location of 62.5% of the full length to 53% of the full length of the RBCC thereby moving the *cg* to where the *ac* is now located resulting in neutral stability.

V. Appendix

A-1. Uncertainty Analysis

An uncertainty analysis of the results was conducted based on the measured results and inherent inaccuracies of the instruments used. Uncertainty is made of precision error and bias error. Precision error is the difference in the same measured value from different runs on separate days of testing of the same RBCC configuration. Bias error is the inherent inaccuracies of the measurement devices used. Table 6 presents the bias error, precision error and uncertainty for the various aerodynamic coefficients.

Table 6. Uncertainty for Aerodynamic Coefficients

Coefficient	Bias Error (averaged)	Precision Error (averaged)	Total Uncertainty
C_L	$\pm 3.84 * 10^{-3}$	$\pm 1.43 * 10^{-2}$	$\pm 1.480\%$
C_D	$\pm 1.14 * 10^{-3}$	$\pm 4.73 * 10^{-3}$	$\pm 0.487\%$
C_l	$\pm 4.73 * 10^{-5}$	$\pm 2.53 * 10^{-4}$	$\pm 0.025\%$
C_m	$\pm 7.83 * 10^{-4}$	$\pm 3.12 * 10^{-3}$	$\pm 0.322\ \%$
C_n	$\pm 6.81 * 10^{-5}$	$\pm 1.90 * 10^{-4}$	$\pm 0.020\%$

The bias error is based on the inherent inaccuracies in the instruments used to measure various parameters in the SWT, such as temperature and pressure transducers. The error is published by the manufacturer of the particular measurement device. Using the following equation the bias error for the coefficient of lift is calculated[6]:

$$B_{C_L} = \left[\left(\frac{\partial C_L}{\partial N_1} B_{N_1}\right)^2 + \left(\frac{\partial C_L}{\partial N_2} B_{N_2}\right)^2 + \left(\frac{\partial C_L}{\partial A_x} B_{A_x}\right)^2 + \left(\frac{\partial C_L}{\partial \alpha} B_{\alpha}\right)^2 + \left(\frac{\partial C_L}{\partial P_d} B_{P_d}\right)^2 + \left(\frac{\partial C_L}{\partial S} B_S\right)^2\right] \quad (1)$$

The equation for C_L based on the outputs from the force balance and other measurement devices is as follows:

$$C_L = \frac{(N_1+N_2)cos\alpha - A_x sin\alpha}{\frac{\gamma}{\gamma-1}\left[\left(\frac{P_0}{P_0-\Delta P}\right)^{\frac{\gamma-1}{\gamma}}\right](P_0-\Delta P)S} \quad (2)$$

This process is repeated for the other four other aerodynamic coefficients based on the different solutions for each of the aerodynamic coefficients using the outputs of the force balance and the pressure transducers.

The precision error is calculated using a Student's t-distribution for the four runs completed on four different days for the same RBCC clean configuration. The Student's t-distribution was done using a confidence interval of 90%. The precision error is a representation of the system's ability to repeat the same data for any given run of the RBCC. By using the Student's t-distribution the variability in random error can be analyzed. The equation used to calculate the precision error is as follows[6]:

$$t * \frac{s}{\sqrt{n}} \quad (3)$$

Where t is the $t - value$ based on the Student's t as a function of α and ϑ, where α is $1 - Confidence\ Interval$ in this case the confidence interval is 90%, and v is the degrees of freedom, s is the standard deviation for the respective aerodynamic coefficient measured over the four runs, and n is $1 - \vartheta$.

Once the precision error and bias error are calculated uncertainty can be calculated. Uncertainty combines both systematic (bias) and random (precision) error together in order to provide the amount of uncertainty in the measured aerodynamic coefficients. In order to calculate the uncertainty of the data collected the following equation was used[6]:

$$Uncertainty = \sqrt{[(Bias)^2 + (Precision)^2]} \quad (4)$$

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